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Remark on Charm Quark Fragmentation to D^{**} Mesons*

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Abstract

The observed D^{**} mesons have $c\bar{q}$ flavor quantum numbers and spin-parity of the light degrees of freedom $s_\ell^{\pi_\ell} = 3/2^+$. In the $m_c \to \infty$ limit the spin of the charm quark is conserved and the $c \to D^{**}$ fragmentation process is characterized by the probability for the charm quark to fragment to a D^{**} meson with a given helicity for the light degrees of freedom. We consider the calculated $b \to B_c^{**}$ fragmentation functions in the limit $m_c/m_b \to 0$ as a qualitative model for the $c \to D^{**}$ fragmentation functions. We find that in this model charm quark fragmentation to $s_\ell^{\pi_\ell} = 3/2^+$ light degrees of freedom with helicities $\pm 1/2$ is favored over fragmentation to $s_\ell^{\pi_\ell} = 3/2^+$ light degrees of freedom with helicities $\pm 3/2$.

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Heavy quark spin-flavor symmetry[1,2] has important consequences for the spectroscopic properties[3] of hadrons containing a single heavy quark Q. In the $m_Q \to \infty$ limit the spin of the heavy quark $\vec{S}_Q$ is conserved. It is convenient for classifying states to introduce the spin of the light degrees of freedom $\vec{S}_\ell = \vec{S} - \vec{S}_Q$. In the $m_Q \to \infty$ limit hadrons containing a single heavy quark Q are labeled by the quantum number s_ℓ and these states come in degenerate doublets with total spins $s_\pm$ that arise from combining the spin of the light degrees of freedom with that of the heavy quark

$$s_\pm = s_\ell \pm 1/2. \tag{1}$$

(An exception is the case $s_\ell = 0$ where there is only a single hadronic state with total spin 1/2.)

Recently Falk and Peskin noted that heavy quark spin symmetry relates fragmentation probabilities for members of these hadron doublets.[4] It implies that the probability, $P^{(H)}_{h_Q \to s, h_s}$, for a heavy quark Q with spin along the fragmentation axis h_Q to fragment to a hadron H in a doublet with spin of the light degrees of freedom s_ℓ, total spin s and total spin along the fragmentation axis (i.e., helicity) h_s is

$$P^{(H)}_{h_Q \to s, h_s} = P_{Q \to s_\ell} p_{h_\ell} | < s_Q, h_Q; s_\ell, h_\ell | s, h_s > |^2, \tag{2}$$

where $h_\ell = h_s - h_Q$. In eq. (2) $P_{Q \to s_\ell}$ is the probability for the heavy quark to fragment to a doublet with spin of the light degrees of freedom s_ℓ. It is independent of the heavy quark spin but will depend on other quantum numbers needed to specify the doublet containing H. p_{h_ℓ} is the conditional probability that the light degrees of freedom have helicity h_ℓ (given that Q fragments to s_ℓ). The probability interpretation implies that $0 \le p_{h_\ell} \le 1$ and

$$\sum_{h_\ell} p_{h_\ell} = 1. \tag{3}$$

Parity invariance of the strong interactions implies that

$$p_{h_\ell} = p_{-h_\ell}. \tag{4}$$

Eqs. (3) and (4) restrict the number of independent probabilities p_{h_ℓ} to be equal to $s_\ell - 1/2$ for mesons and s_ℓ for baryons. At the hadron level parity invariance of the strong interactions implies that

$$P^{(H)}_{h_Q \to s, h_s} = P^{(H)}_{-h_Q \to s, -h_s}. \tag{5}$$

Heavy quark spin symmetry reduces the number of independent fragmentation probabilities. For mesons with spin of the light degrees of freedom s_ℓ the fragmentation probabilities $P^{(H)}_{h_Q \to s, h_s}$ are expressed in terms of the $s_\ell - 1/2$ (s_ℓ for baryons) independent p_{h_ℓ}'s and $P_{Q \to s_\ell}$.

For the D and D^* mesons $s_\ell^{\pi_\ell} = 1/2^-$ and eqs. (3) and (4) imply that $p_{1/2} = p_{-1/2} = 1/2$. The relative fragmentation probabilities.

$$P^{(D)}_{1/2 \to 0,0} \quad : \quad P^{(D^*)}_{1/2 \to 1,1} \quad : \quad P^{(D^*)}_{1/2 \to 1,0} \quad : \quad P^{(D^*)}_{1/2 \to 1,-1}, \tag{6}$$

are

$$1/4 \quad : \quad 1/2 \quad : \quad 1/4 \quad : \quad 0 \quad . \tag{7}$$

Eq. (5) determines the fragmentation probabilities for a helicity $-1/2$ charm quark in terms of those above. The relative fragmentation probabilities for the three D^* helicities agree with experiment, however, the prediction that the probability for a charm quark to fragment to a D is 1/3 the probability to fragment to a D^* does not. Part of the origin of this violation of heavy quark symmetry may be in the $D^* - D$ mass difference which suppresses fragmentation to the D^*.

Excited spin-one and spin-two charmed mesons $D_1(2420)$ and $D_2^*(2460)$ have been observed experimentally. Their properties suggest that they are members of a

doublet with spin-parity of the light degrees of freedom $s_\ell^{\pi_\ell} = 3/2^+$. These states are sometimes referred to as D^{**} mesons. For this multiplet eqs. (3) and (4) imply that there is only one independent conditional probability p_{h_ℓ}. Falk and Peskin take it to be $w_{3/2}$, the conditional probability to fragment to helicities $\pm 3/2$, and write

$$p_{3/2} = p_{-3/2} = \frac{1}{2} w_{3/2}, \tag{8a}$$

$$p_{1/2} = p_{-1/2} = \frac{1}{2}(1 - w_{3/2}). \tag{8b}$$

Eq. 2 implies that the relative fragmentation probabilities[4]

$$P^{(D_1)}_{1/2\to 1,1} \quad : \quad P^{(D_1)}_{1/2\to 1,0} \quad : \quad P^{(D_1)}_{1/2\to 1,-1} \quad :$$

$$P^{(D_2^*)}_{1/2\to 2,2} \quad : \quad P^{(D_2^*)}_{1/2\to 2,1} \quad : \quad P^{(D_2^*)}_{1/2\to 2,0} \quad : \quad P^{(D_2^*)}_{1/2\to 2,-1} \quad : \quad P^{(D_2^*)}_{1/2\to 2,-1}, \tag{9}$$

are

$$\frac{1}{8}(1 - w_{3/2}) \quad : \quad \frac{1}{4}(1 - w_{3/2}) \quad : \quad \frac{3}{8} w_{3/2} \quad :$$

$$\frac{1}{2} w_{3/2} \quad : \quad \frac{3}{8}(1 - w_{3/2}) \quad : \frac{1}{4}(1 - w_{3/2}) \quad : \quad \frac{1}{8} w_{3/2} \quad : \quad 0. \tag{10}$$

Total fragmentation probabilities are given by multiplying eq. (10) by $P_{c\to 3/2}$.

Eq. (10) predicts that the ratio of D_1 to D_2^* production by charm quark fragmentation is 3/5, independent of $w_{3/2}$. Assuming that D^{**} decays are dominated by $D^{(*)}\pi$ final states the experimental value of this ratio is close to unity[5] (with an error at the 20% level). However, Eichten, et al., have suggested that $D^{**} \to D^{(*)}\pi\pi$ decays are also important.[6] Experimentally the probability to fragment to helicity $\pm 3/2$ light degrees of freedom is small, i.e., $w_{3/2} \lesssim 0.24$ at the 90% confidence level.[4] In this brief report we show that constituent $q\bar{q}$ pair production by a virtual gluon is a fragmentation process that produces a small value for $w_{3/2}$.

The fragmentation functions for $b \to B_c^{**}$ were computed in Ref. [7] using perturbative QCD. They are of order $\alpha_s^2(m_c)$ and arise from a single virtual gluon producing a $c\bar{c}$ pair. Taking the limit $m_c/m_b \to 0$, of the results in Ref. [7] for fragmentation to the spin-2 B_c^{**} state, gives [8]

$$w_{3/2} = 29/114. \tag{11}$$

Eq. (11) is our result. The probability to fragment to helicities $\pm 3/2$ is roughly one-third the probability to fragment to helicities $\pm 1/2$. This suppression may arise because fragmentation to helicity $\pm 3/2$ light degrees of freedom requires a non-zero opening angle with respect to the fragmentation axis to conserve total angular momentum.

The value of $w_{3/2}$ in eq. (11) arose from perturbative QCD. Of course the $c \to D^{**}$ fragmentation process is nonperturbative. Nonetheless, we find it interesting that a simple physical mechanism can give a small value for $w_{3/2}$. If the value of $w_{3/2}$ is measured to be roughly equal to 0.25 then production of a constituent $q\bar{q}$ pair by a virtual gluon may provide a reasonable qualitative picture for the $c \to D_2^{**}$ fragmentation process.

References

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8. There are several typographical errors in eqs. (60) and (61) of Ref. [7]. The correct expression for W_2 in eq. (60) is minus that given in Ref. [7] and in eq. (61) the correct expression for W_0^0 is $W_0^0 = (z^2\alpha_2^2 - 2z^2\alpha_2 - 2z\alpha_2 + z^2 + z + 1)^2(1-z)/12$.